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SIMULATION OF PRIMARY SERVICE DEGRADATIONS FOR CRISIS MANAGEMENT OPERATIONS

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ABSTRACT:
In this work, we present a specific application implemented within a Decision Support System (DSS) for risk analysis of (inter)dependent Critical Infrastructures (CI) under development within the EU FP7 CIPRNet Project. The DSS is able to: 1) predict damages on the CI physical components caused by extreme natural events as heavy rains and flooding, 2) show the cascading effect on the related services in the CI; and 3) estimate the resulting consequence on the social system (e.g., citizens' well-being, economic activities). A central role in the CI system of systems is played by the electrical, water, and telecommunication systems: the availability of the SCADA system to perform remote operations (tele-control) is required to ensure electrical network stability and thus, an efficient energy supply to the consumers. Tele-control operations bi-directionally couple the telecommunication and electrical networks. Thus, restoration actions in a fully dependent system formed by these CI cannot disregard an assessment of the state of functioning of both infrastructures. Services outages of these CI generate cascading effects on other systems, producing large consequences for the availability of primary services (e.g., hospitals). To measure such consequences, we employ an interdependency model to estimate the degradation of infrastructure services due to the loss of electricity and telecom services. The developed application is applied to a case study involving an electric-telecommunication system, a water distribution system and hospitals.
The proposed solution introduces a common formalism for the description of CI and their dependencies and integrates an interdependency simulator allowing the automatic building of large scenario models and the execution of simulations that can support CI operators and Emergency Managers during a crisis.

KEYWORDS:
Risk Analysis, Critical Infrastructures, Decision Support System, Power Grid, SCADA

1. INTRODUCTION

Critical Infrastructure Protection (CIP) is a concept that relates the preparedness and the response to severe incidents involving critical infrastructures of all countries. Events such as 9/11, Katrina, and others, showed that considering infrastructures separately was not sufficient to prepare for and respond to large disasters in an effective manner that prioritizes overall societal impact over individual infrastructure states. When a specific perturbation, such as an earthquake, hits a system of Critical Infrastructures (CI), the "primary effects" or "No-CI related Consequences" of the damages produced by the event can be expressed in terms of the number and the economic value of the collapsed buildings, and the number of casualties or the economic losses related to the disruption of a given production. In addition, there might be "secondary effects or "CI related Consequences" connected to the degradation of CI services (e.g., electricity, water, gas) that can be exacerbated by cascading effects. In general, No-CI Consequences are limited to the area affected by the natural events whereas the area to which CI-related Consequences refer to can be much larger than the area affected by these natural events. A typical example of this situation is the 2003 Italian blackout where the large CI-related Consequences caused by an extended and prolonged electrical blackout were triggered by the collapse of a high tension pylon that produced a very small No-CI Consequences blackout. Prediction and a rapid assessment of both types of consequences in a critical scenario can be a major breakthrough for increasing preparedness and mitigation actions. To this end, a major goal could be represented by a correct prediction of the course of events, starting from the prediction of the occurrence of natural hazards and their strengths to the resulting effects that they will produce due to a reduction in supplied services and the consequences they have on relevant areas of societal life. The realization of a similar object, cast in the form of a Decision Support System (DSS), is one of the objectives of the EU FP7 CIPRNet project. The designed DSS implementing the above mentioned risk assessment workflow, can be used to both predict the extent of the expected crisis used to "weigh" the efficacy of the proposed mitigation and to predict the subsequent healing actions, therefore being a valuable tool for supporting emergency managers, such as CI operators, Civil Protection and fire brigades. Whether No-CI related Consequences can be evaluated on the basis of the damages, the transformation of them into CI related Consequences is much more complex and requires the introduction of a further term, which we indicate as "impact". Impact identifies the resulting effects of damages on the services produced by the CI (e.g., the damage of an electric distribution substation that produces an electric outage in a city area for a given period of time as well as disruptions in the telecommunication network). After creating the complete assessment of the impact, one can evaluate the CI related Consequences by transforming impact into well-being societal variation. The proposed DSS advances the state of the art by including in a unique framework, the prediction of natural hazards and the estimation of their effects on CI and societal life.

In Rosato et al. (2015), we showed how the DSS is able to estimate the consequences for the citizens due to the degradation of technological services. To this aim, we defined a Service Access Wealth Index (SAWI) based on consumption data of Italian residents and we related the possible loss of electricity service in specific parcel areas to the well-being of citizens of different age groups. In the present paper, we show how the predicted degradation of services can be used to propagate the dependencies among a power grid, a SCADA system and a water distribution network to quantify the reduction of primary services delivered by a hospital. The DSS uses an interdependency simulator to model and simulate the dependencies among the different CI domains and primary services. In particular, the work presented here illustrates how the proposed approach faces some of the main challenges that need to be considered in modeling and simulation of CI related urban crisis scenario i.e.: i) data gathering; ii) data homogenization; and iii) simulation of large models. A major contribution of this work is that the data from the electrical system infrastructure is obtained directly from the utility company database. The simulation scenario is established automatically from data mined from this database and the weather prediction layer.

This paper is structured as follows. Section 2 describes related work in the area. Section 3 presents the main functionalities of the DSS required to implement the risk assessment workflow. Section 4 focuses on the DSS impact and consequence analysis modules and present the procedure that allows to propagate the predicted damages in the considered CI in terms of short time scale impact and effects on the delivery of primary services and to define possible mitigation strategies of the crisis. Section 5 presents a case study where we apply our methodology to estimate the consequences to hospitals in an area of Rome due to disruptions occurring in the electric-telecommunication system and water distribution system. Finally, Section 6 draws some conclusions and ideas for future work.

2. RELATED WORK

This section discusses related work on DSS for the estimation of primary effects of natural hazards, models for impact assessment, and approaches for evaluating the CI related consequences, i.e., the effects on the operability of primary services due to the loss of CI services.

Kamissoko et al. (2013) developed a DSS that estimates the vulnerability of infrastructure networks taking into account interdependency phenomena. Their DSS models network dependencies through graph theory and is able to infer vulnerable areas, critical components and the most threatened stakes (e.g., a firm, a habitation, a government institution) by specifying the probability of a natural hazard and the state of the system. The European UrbanFlood (2012) was aimed at developing an Early Warning System (EWS) for the prediction of flooding in near real time. The system was validated in the context of dike performance in an urban environment and uses a sensor monitoring network to assess the condition and likelihood of failures. The system employs flooding specific modules, including dike breach evolution and flood-spreading models. In the context of the European Earth observation program, Copernicus (2010), a European Flood Awareness System (EFAS) was developed to produce European overviews on ongoing and forecasted floods to support the EU Mechanism for Civil Protection. The Italian national project SIT_MEW (2010) focused on the implementation of an EWS, to predict potential impact of seismic events on structures and buildings immediately following an earthquake. These previously proposed DSS, however, do not take into account the interplay of environmental forecasts and interdependency phenomena of CI.

Regarding the latter, Ouyang (2014) has reviewed all the research in modeling and simulation of interdependencies of CI according to six branches: (i) empirical; (ii) agent based; (iii) system dynamics based; (iv) economic based; (v) network based; and (vi) other approaches based on High Level Architecture (HLA) and Petri-net techniques. Our DSS employs network-based approaches, which models the performance of each network through topological properties of the network such as the connectivity loss, the number of normal or failed physical components, the duration of components unavailability, and the number of customers served or affected. Other network based approaches include De Porcellinis et al. (2008) who tested mitigation and healing strategies modelling of an electrical network with a DC power flow solution, and finding the relationship between an Internet Quality of Service (QoS) index and its effect on the QoS of the electrical network. They used a data packet model to model the Internet communication layer.

Our DSS is interacting with the real-time, time-domain simulator, i2Sim, developed by Martí (2008, 2014), which solves the interdependencies among CI in a system, and determines the optimal allocation of resources for all CI in terms of a global system objective (e.g., save human lives). i2Sim has been applied in several real cases including the campus of the University of British Columbia (UBC), the downtown area of the city Vancouver, and the Guadeloupe Island. i2Sim's conceptual and solution framework is very general and can accommodate for non-linear relationships among systems of dissimilar nature, thus it is able to model a small city with many different interdependent infrastructures.

3. OVERVIEW ON THE CIPRNet DECISION SUPPORT SYSTEM

The CIPRNet DSS can be logically represented in terms of five functional components (Bi), which leverage on a large database containing GIS data of CI elements, assets, geographical, social, and economical information of the area under control. These are:

- **Monitoring of natural phenomena (B1)**: This functional block acquires geoseismic, meteorological forecasts and now-casting data, and other sensor field data when available.
- **Prediction of natural disasters and events detection (B2)**: This block, based on information of B1, predicts, within an estimated temporal horizon, the strength of a limited set of natural phenomena occurring in the specified area.
- **Prediction of Physical Harm Scenarios (B3)**: This block evaluates the probability that each CI component, located in a certain area, can suffer a certain amount of damage if hit by the predicted natural events with a certain strength. The association "event strength-damage" of a physical component c_i of the *x*-th CI by a threat manifestation T_j is performed by considering the intrinsic vulnerability of c_i w.r.t. the intensity of T_j (output of B2). The outcome is a set of affected CI physical components with the extent of the estimated physical damages called *Physical Harm Scenario* (PHS) defined as:

  $$PHS = (c^{\intercal}, d^{\intercal}) \quad (1)$$

  where $c^{\intercal} = (c_1^{s_1}, \dots, c_R^{s_R})$ is the set of CI components belonging to the infrastructure s_i that, at time t=0, are expected to receive an over-threshold probability to be damaged; $d^{\intercal} = (d_1^{s_1}, \dots, d_R^{s_R})$ is the set of the extent of estimated damages for each CI component; R is the number of possible damaged components; $s_i \in \{1, \dots, U\}$ and U is the total number of CI considered.
- **Estimation of Impact and Consequences (B4)**: This block estimates the impact that the PHS may

produce on the services delivered by the CI and the resulting consequences for society. Based on the PHS and models to propagate damages of the physical components across different CI, the DSS is able to produce an *Impact Vector* I(t), which contains the set of QoS functions Q(t) associated with each CI. The generic Impact Vector estimated over time T of the crisis is defined as:

$$I(t) = (\Delta Q(T)^{\intercal}) \quad (2)$$

where: $\Delta Q(T) = (\Delta Q_1^{v_1}(T), \dots, \Delta Q_L^{v_L}(T))$ is the set of the QoS variations of the CI over the time T; L is the number of services considered and $v_i \in \{1, \dots, U\}$. In Section 4.2, we define the Consequence Vector $C(t)$ that contains the consequences due to the reduction of CI services by introducing the concept of wealth of primary services.

- **Support of efficient strategies to cope with crisis scenarios (B5)**: This block provides crisis managers with a decision list of actions in those cases where the DSS can provide further information needed to support a crisis solution.

In the next Section, we focus on B4 by first recalling our approach to estimate the Impact Vector in a power grid and then present our metric to assess the related consequences on the primary services due to the degradation of power services.

4. CRITICAL INFRASTRUCTURE RELATED CONSEQUENCES

4.1. Estimation of Impact

Starting from the predicted damages of CI physical components, B4 first computes the reduction of QoS of the dependent networks and then the related consequences for the delivery of primary services. To take into account the different time scales of the dependency mechanisms, the Impact evaluation module executes two consecutive procedures called Pre-Impact Assessment and Comprehensive Impact Assessment respectively.

In the Pre-Impact Assessment, strongly coupled infrastructures such as the electrical and the telecommunication networks are considered. Their strong coupling activates dependency mechanisms holding in the short time scale (from a few minutes up to one hour). The outcome of this procedure is the expected outage duration of the electrical distribution substations. In the Comprehensive Impact Assessment, dependencies among all the infrastructures (e.g., power grid with water distribution) that present a larger latency are analyzed. During very short times scales, such CI could be considered as “decoupled” from the previously cited infrastructures, in a sort of adiabatic approximation. This procedure takes as an input the expected outage duration of the distribution substations of the considered scenario calculated in the Pre-Impact assessment block and propagates to other CI.

4.1.1 Pre-Impact Assessment

The estimation of impact is performed through a network based procedure developed by Tofani et al. (2015) that takes into account the interdependency mechanisms existing among a power grid and its SCADA system. This approach is based on the real properties of the electrical distribution grid of Rome consisting of several High Voltage (HV) Primary Substations (PS) and Medium Voltage (MV) Secondary Substations (SS) that are connected to PS through backbones (consisting of two semi-backbone or SB) according to a serial configuration. Each SS can satisfy the electrical demand of a district approximately composed of 100 households. The interdependency phenomena between the two CI stand as the electrical SS supply energy to specific Telecom devices, called Base Transceiver Stations (BTS) that in turn ensure tele-control capability to the electrical grid. In addition, the BTS installed in each mobile antenna, requires energy to function, which is provided through the electric SS. Considering their strong interdependency, damages occurring in the electrical SS and/or the BTS, can cause disruptions that hold in the short time scale (from a few minutes up to some hours) leaving people without power and mobile communication services. Based on the interdependency information regarding the two systems and the PHS (periodically estimated by the DSS B3) including the possible damaged electrical SS and Telecom BTS, the impact estimation procedure emulates the restoration procedure of the electrical operator to infer the possible evolution of the electric grid in the medium term. In particular, the procedure identifies those SS that, because of the loss of tele-control capability, require manual intervention and those that can be reconnected via the electric SCADA system. Then, considering the average time required by the emergency teams (that are limited in number) to reach specific electric SS and reconnect the related users (e.g., using UPS), the procedure estimates the Impact Vector I(t) in terms of the electric power profiles that are generated by each specific SS. It is clear that, according to the sequence of manual actions executed by the emergency teams, there might be different impact outcomes. Some SS can supply several households w.r.t. other ones, or the reactivation of some SS are necessary for other restoration and/or can enable some actions to be performed more rapidly. Let K be the number of available emergency teams and M be the number of electric SS to be reconnected. We define the ordered sequence $O_l = (SS_1^l, SS_2^l, \dots, SS_M^l)$ of SS that are reconnected by the l-th emergency team with $l \in \{0,1,\dots,K\}$. Thus, depending on the sequences O_l implemented to cope with a crisis, the DSS estimates the related consequences for the delivery of primary services as their functionality is influenced by the availability of services delivered by CI.

4.1.2 Comprehensive Impact Assessment

In the Comprehensive Impact Assessment procedure, all dependencies from the electrical and telecommunication domains are considered in order to have a complete assessment of the considered crisis scenario. An i2Sim model is constructed and executed to simulate the dependencies among the different domains. Figure 1 shows the full process of converting the data from the DSS DB (storing CI dependency data coming from different sources and format) into the i2Sim DB, constructing the i2Sim model and delivering it to i2Sim engine for interdependency simulation. The i2Sim Database Integration tables (i2Sim DB tables) represent a common data formalism that stores and homogenizes data of different CI networks. The i2Sim DB tables are read by the i2Sim model builder, which in turn, creates a model that can be simulated using the i2Sim engine. The SS Power Profiles are treated as scenarios and run with the i2Sim model file. Each profile is converted into an input file in XML format, which the i2Sim engine reads, analyzes and processes. The final results are then stored into output files also in XML format. i2Sim runs multiple scenarios in real time based on the changing inputs that the scenario profile provides. Therefore, two types of output files are generated. The first file is an accumulation of all time steps throughout the total simulation runtime. This output file represents the QoS of all entities considered in the scenario (e.g., hospitals, water pumps, electricity). The second file is a profile of each individual time step, allowing the user to assess the situation at any moment. Based on the given objective of the problem, the i2Sim output files detail the impact of distributing resources to one infrastructure over another, thus observing the consequence of each action.

i2Sim considers the dependencies among CI through its Human Readable Table (HRT). The HRT table homogenizes the different data sources and correlates the resources and factors that will affect the production of a given system unit (e.g., factory, hospital, substation). The input vectors (columns of the table) are linearly independent eigenvectors, allowing elements of different nature to affect the operating level of the system unit under linear or nonlinear relationships. Based on the level of these inputs, i2Sim computes the operating level of that unit and provides an output based on the limiting physical, structural, or operational actions. For example, in a hospital unit, the inputs could be electricity, water, number of injured people, number of doctors and nurses, stress level of the personnel, and the output is the number of patients treated by the unit. If there was a scarcity in water from the water pumping station that fed the hospital, the number of patients treated would be limited based on the amount of water fed to the hospital.

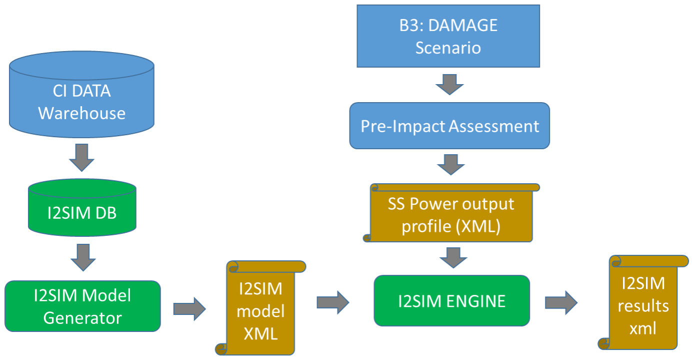

Figure 1 Comprehensive Impact Assessment data flow.

4.2 Estimation of Consequences

In order to define the significance of the impact produced by the disruption or destruction of one (or more) CI, the European Council Directive 2008/114/EC (see European Commission, 2008) proposes that such effects should be assessed in terms of cross-cutting criteria. These include: (i) Casualty criterion assessing the potential number of fatalities or injuries; (ii) Economic effects criterion assessing the significance of economic loss and/or degradation of products or services including the potential environmental effects; and (iii) Public effects criterion in terms of the impact on public confidence, physical suffering and disruption of daily life including the loss of essential services.
Based on the latter, we summarized in a unique list of criteria, a number of domains that express the criteria above mentioned whose well-being reduction could be estimated both in the No-CI and in the CI-related Consequence analysis. We defined four criteria (called CA Criteria) as the following:

- **CA Citizens Criterion.** It relates to population, to citizens and encompasses the reduction of well-being to the most vulnerable population layers (e.g., elderly people, children).
- **CA Primary Service Criterion.** It relates to the primary services that affect the wealth and the well-being of the population (i.e., hospitals, schools, public offices, and public transportation).
- **CA Economy Criterion.** It relates with the economic losses that depend, in turn, on the integrity and the lack of production hours/days due to services outages. (i.e., primary, secondary and tertiary sectors).
- **CA Environment Criterion.** It relates to the environmental damages that can be produced by disruptions (e.g., landslides, flooding etc.) but also by secondary effects (e.g., pollution, leakages from plants) on specific assets (i.e., forests, protected areas, sea and shores, basins).

The DSS provides an estimate of the No-CI and CI related consequences performed according to the previously defined criteria, in the time interval predicted for the crisis. In particular, the impact estimation module will result in the prediction of the loss or reduction to the QoS of one or several CI services. This is provided in the form of a vector $Q_i(t)$ for each service i coming from the damage of CI physical components. On the basis of this data, the consequence estimation module generates the related consequences in terms of wealth variations of each criterion. Such quantities are provided as a Consequence Vector C(t) defined in the following:

$$C(t) = \{C^{cit}(t), C^{ser}(t), C^{eco}(t), C^{env}(t)\} \qquad (3)$$

where $C^{cit}(t)$, $C^{ser}(t)$, $C^{eco}(t)$, and $C^{env}(t)$ represent the consequences for citizens, primary services, the economy and the environment respectively, predicted over time *t*. In this paper, we limit our analysis to the evaluation of the consequences on primary services. To this aim, in the next Section, we define a metric that evaluates the level or *wealth* of primary services based on the variation of specific CI technological services.

4.2.1 Wealth Index of Primary Services

Limiting our analysis to the wealth of primary services delivered by hospitals, let us define the wealth

$\boldsymbol{W(t, h_j)^{ser}}$ of the **CA Primary Service Criterion** related to hospital h_j as a function of the available technological services k that are required by the hospital to deliver its service:

$$W^{ser}(t, h_j) = M(h_j) f_{h_j}[Q_1(t), \ldots, Q_N(t)] \tag{4}$$

where:

- N is the number of the technological services, which contribute to the delivery of the primary service of hospital h_j.
- $M(h_j)$ is the maximum number of patients healed that can be delivered by hospital h_j.
- $Q_k(t)$, with $k \div 1, N$ and $0 \leq Q_k(t) \leq 1$ measures the QoS of service k over time where $Q_k(t) = 1$ represents the full availability of service k and $Q_k(t) = 0$ the unavailability of service k.
- $f_{h_j}[Q_1(t), \ldots, Q_N(t)]$ with $0 \leq f_{h_j}(\cdot) \leq 1$ relates the QoS of the N technological services service to the availability of hospital h_j to deliver $M(h_j)$ healed patients per hour.

4.2.2 Consequence Vector

In the following, we define the consequence $C^{ser}(T, h_j)$ as the wealth variation of hospital h_j associated with the variation of the QoS of the technological services k over the time duration T of the crisis. Let us first define the maximum wealth $W_0^{ser}(h_j)$ during time T with full availability of services k:

$$W_0^{ser}(h_j) = M(h_j) \tag{5}$$

We can now define the $C^{ser}(T, e_j)$ as the difference between the maximum wealth $W_0^{ser}(e_j)$ and the effective wealth integrated on time duration T normalized w.r.t. $W_0^{ser}(h_j)$ as follows:

$$C^{ser}(t, h_j) = \frac{W_0^{ser}(h_j) - M(h_j) \int_0^T f_{h_j}[Q_1(t), \ldots, Q_N(t)] dt}{W_0^{ser}(h_j)} \tag{6}$$

Considering a generic hospital that requires N=3 technological services (i.e., electricity, water and telecommunication), we have:

$$W_0^{ser} = W_0^{ser}(h_j) \tag{7}$$

$$C^{ser}(T) = \frac{W_0^{ser} - W_0^{ser} \int_0^T f[Q_1(t), \ldots, Q_3(t)] dt}{W_0^{ser}} \tag{8}$$

The resulting consequence $C^{ser}(T)$ is a number varying between 0 and 1 (with 0 indicating no consequences and 1 severe consequences) expressing the possible variation of wealth of a hospital over time T of the crisis due to the degradation of the electricity, water and telecommunication service.

5. CASE STUDY

A real case study is shown in Figure 2 where we represent an area of Rome consisting of:

- A section of the electric distribution grid with 9 electrical PS (PS_1 – PS_9) and 164 electrical SS (SS_1 – SS_{164}) serving specific census parcels, where the orange circles denote the remotely controlled SS.
- A Telecommunication network with 6 BTS providing tele-control capability to specific SS.
- A water distribution network with 3 pumping stations.
- 3 hospitals.

The Telecom BTS are supplied power by the electric SS. There are also three water stations that are supplied by the electric SS, which in turn provide water to three hospitals. Hospitals receive electricity from one (or more) electric SS and water from the pumping stations. The hospitals cover the needs of citizens according to the areas shown in Figure 3. Six main assumptions are made in the case study: (i) the PHS built on weather forecasts estimates a disconnection of SS_3, SS_{84} and SS_{124}; (ii) only one emergency team is available for the electric operator to reach and reconnect the isolated SS; (iii) no power backup is available to the BTS, pumping stations and hospitals; (iv) the moving time required by the emergency team to reach the electric SS is negligible; (v) one hour is the average time to perform a manual intervention in any SS of the district of Rome and (vi) the average time to perform tele-control operations (e.g., opening or closure of breakers) is negligible.

Considering such assumptions and the properties of the electrical grid, the impact estimation procedure described in Section 4.1 suggests the following subsequent events:

- At time t_1=0, SS_3 and SS_{84} and SS_{124} are disconnected;
- At time $t_2 \approx 0$, all electric SS in SB_{01}, SB_{19} and SB_{11} will automatically disconnect (due to the failure of SS_3, SS_{84} and SS_{124}).

At this stage, only some electric SS are reactivated:

- SS_1 through the direct connection to PS_1
- SS_{81} through the direct connection to PS_2
- SS_{120} and SS_{121} are reconnected through tele-control because BTS_6 is working
- SS_4 - SS_{27} are not reconnected through tele-control because BTS_7 is not working due to the disconnection of SS_{124} which in turn causes the disconnection of SS_{123}
- SS_{126}, SS_{127}, SS_{125} are not reconnected through the closure of the normally open switch connecting SB_6 and SB_{19} as SS_{60} receive tele-control through BTS_{07}, which in turn, is not working.
- SS_{123} and SS_{122} are not working due to the disconnection of SS_{124}.

Considering that some electric SS cannot be reconnected through tele-control actions, a manual intervention to be performed by the emergency team is planned via the impact estimation module. In addition, considering that there is only one emergency team, a choice about which manual intervention to be implemented first should be made by the electric operator. In Figure 3, we report the Impact Vector I(t) in terms of QoS reduction related to the following sequences: $O_1 = \{SS_{84}, SS_3, SS_{124},\}$, $O_1^* = \{SS_{124}, SS_3, SS_{84}\}$.

Considering O_1, the following events are generated:

i. SS_{84} is reactivated manually in about one hour;
ii. SS_{82} - SS_{85} are now supplied;
iii. SS_3 is reactivated manually in about one hour;
iv. SS_2 is now supplied;
v. SS_{124} is reactivated manually in about one hour;
vi. SS_{123} and SS_{122} are now supplied with the effect that BTS_7 provides tele-control capability;
vii. SS_4 - SS_{27} are reactivated through tele-control operations (due to the reactivation of BTS_7) with the effect that WS_3 is working;
viii. SS_{126}, SS_{127}, SS_{125} are reconnected to SS_{60} through tele-control operations.

Considering O_1^*, the following events are generated:

i. SS_{124} is reactivated manually in about one hour;
ii. SS_{123} and SS_{122} are now supplied with the effect that BTS_7 provides tele-control capability.
iii. SS_4 - SS_{27} are reactivated through tele-control operations (due to the reactivation of BTS_7) with the effect that WS_3 is working;
iv. SS_{126}, SS_{127}, SS_{125} are reconnected to SS_{60} through tele-control operations;
v. SS_3 is reactivated manually in about one hour;
vi. SS_2 is now supplied;
vii. SS_{84} is reactivated manually in about one hour;
viii. SS_{82} - SS_{85} are now supplied.

Based on the Impact Vector I(t) produced by the Impact Estimation module for the two sequences, the related consequences $C^{ser}(T)$ are estimated as the wealth variation of the hospital (see eq. 8) delivered over the time duration T = 4h of the crisis. Because only SS_1, SS_2, SS_7, SS_{89}, SS_{90}, SS_{135}, SS_{140} and SS_{141} are feeding electricity into the water station or directly the hospital, the following discussion will focus on these SS and all CIs connected to them.
Two scenarios are created based on the provided power profiles shown in Figure 4. In Scenario 1, both SS_2 and SS_7 are down for 2 hours. After 2 hours, only SS_2 is reactivated. Because both SS_2 and SS_7 feed H_3, although SS_2 is operating at full capacity after 2 hours, the hospital cannot operate due to the limitation from SS_7 being disconnected, as SS_7 supplies water to the hospital. After 3 hours, when SS_7 is reactivated, the water facility is restored and the hospital can operate at its full capacity.
In Scenario 2, SS_7 is reactivated after 1 hour, but SS_2 is reactivated after 2 hours. Therefore, after 1 hour, H_3 cannot operate, because it is limited by the electricity supplied by SS_2. Only after SS_2 is reactivated after 2 hours, H3 can operate at full capacity.
Figure 5 shows the resulting consequences $C^{ser}(T)$ in terms of operability of the hospital. These results show that only H_3 is impacted by failures and interdependency phenomena. In addition, results show that, in order to have H_3 operate at its full capacity, one cannot focus on single factors but the whole system's interdependencies need to be considered. In this case in particular, both SS_2 and SS_7 must be reactivated for the hospital to begin working at full capacity as H_3 is dependent on electricity from both SS_2 and SS_7.

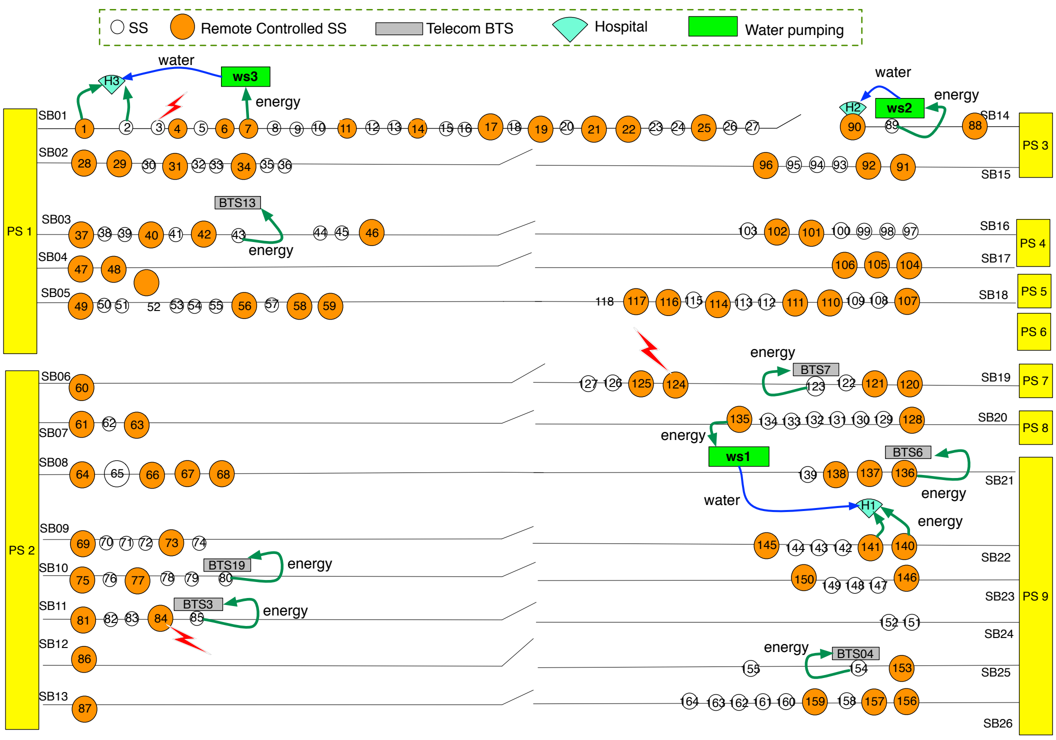

Figure 2: Case study: Representation of the resources exchanged among the different CIs.

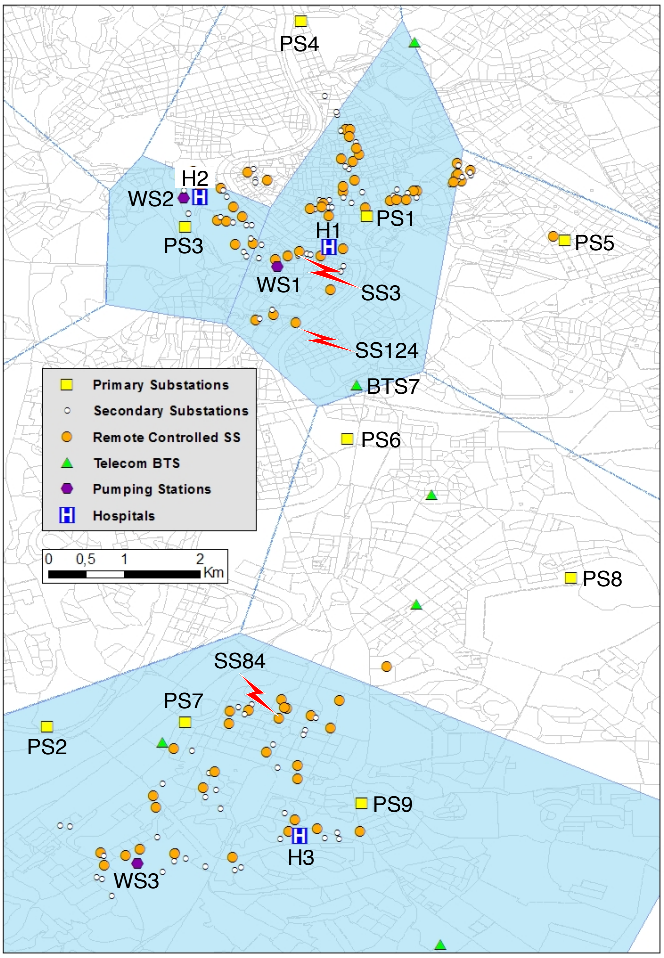

Figure 3. Case study: GIS representation.

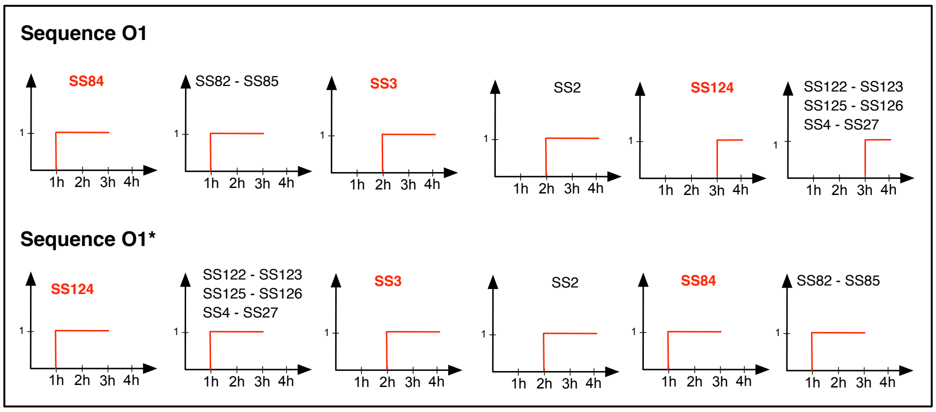

Figure 4. Case study: Power profiles of the SS.

6. CONCLUSIONS

The proposed Decision Support System (DSS) employs modeling and simulation techniques based on weather forecasts and interdependency properties of the electrical and telecommunication grid to estimate the reduction of primary services delivered by hospitals affected by electric and telecom outages in a city area. The case study shows how the DSS may be able to suggest actions to decision makers that would not be considered by the individual contingency plans of the separate infrastructures (which usually do not include interdependencies with the other infrastructures). Future work will focus on the extension of the approach to consider additional primary services (e.g., public transportation).

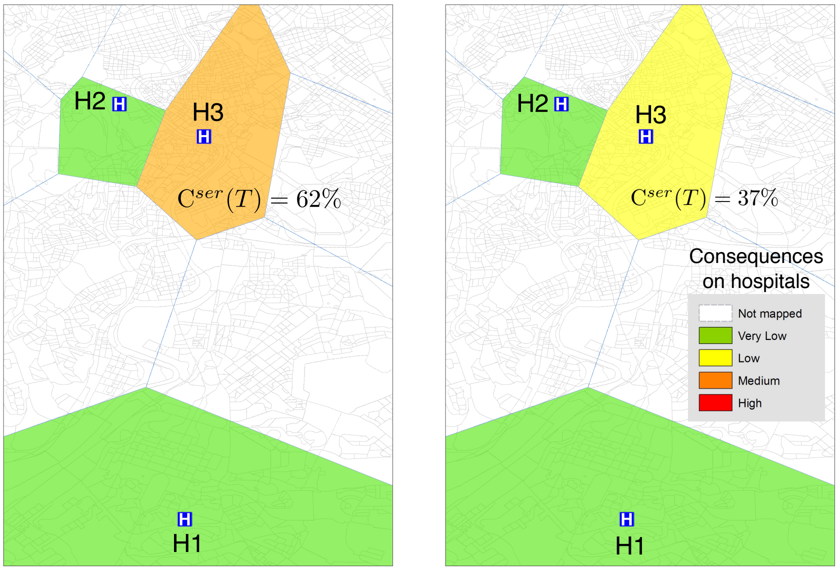

Figure 5. Case study: Consequences on three hospitals.

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